Instrumentation for Dark Energy Surveys

Gregory Tarlé
University of Michigan
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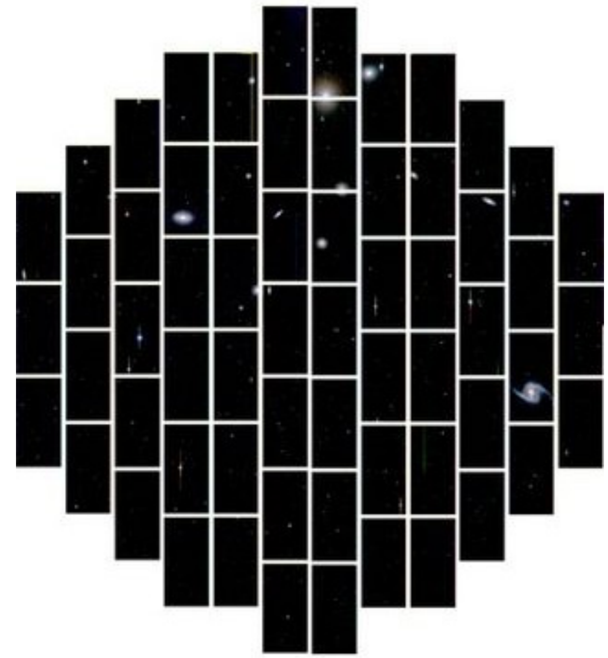
Enabling Technologies for Stage IV Dark Energy Surveys

- Four Techniques (DETF) – Supernovae (SNe) , Weak Lensing (WL), Clusters and Baryon Acoustic Oscillations (BAO)
- Ground based BAO Stage IV possible (e.g. DESI), space may offer larger sky coverage.
- Cluster cosmology gains no major advantage from space environment.
- SNe and WL can benefit greatly from space environment.
  - Precision NIR photometry extends leverage on equation of state to high z for SNe. Spectroscopy in vis-NIR reduces systematic errors.
  - Stable PSF on space platform enables precise shape measurement for WL (Requires many small pixels, excellent photo-z (multiple filters), spectroscopic training set in NIR)
- Detector response characterization/understanding to control systematic errors at ~ 1% level (photometry), required to achieve Stage IV FoM.

DES “First Light” Image



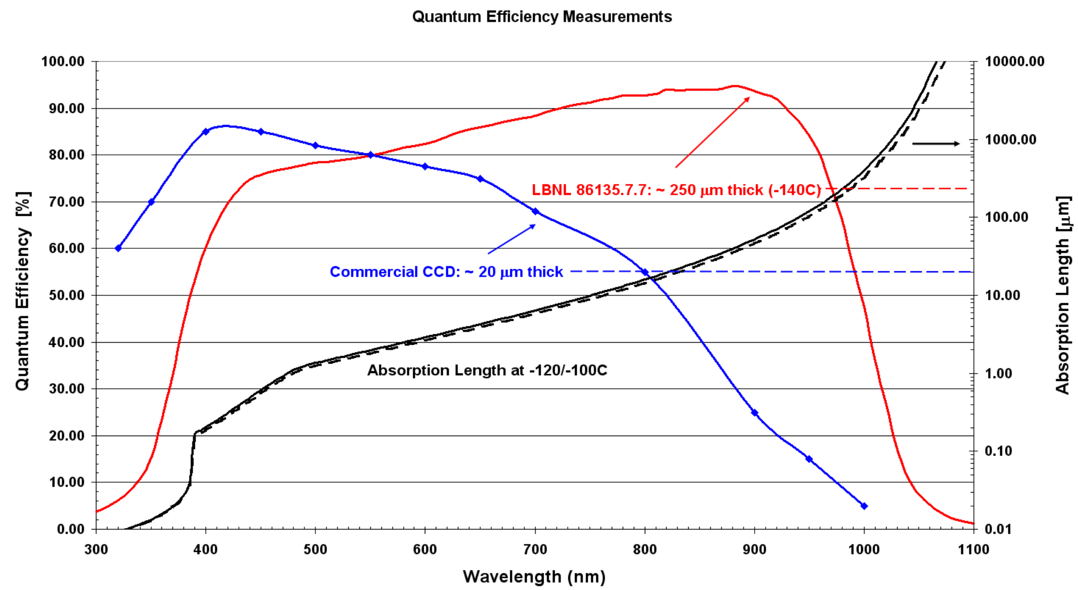
Detector R&D Critical for DE Missions

- Intensive DoE-supported R&D has enabled current DE missions.
  - Fully depleted red-sensitive CCDs developed by LBNL currently in use for DES and to be used for DESI…
  - Detailed studies of HgCdTe FPAs has led to greatly improved properties (QE, read noise, dark current…) and has led to a new detailed understanding of photometric response.
- Examples to follow…

Improved Si CCD Technology

QE improvements

- **Red wavelengths require thicker devices, higher T**
  - enables NIR SNe spectroscopy $1 < z < 2$ for BAO spectroscopic surveys. 20% increase in QE at 1 µm ⇒2 x faster survey, avoids HgCdTe hybrid FPAs



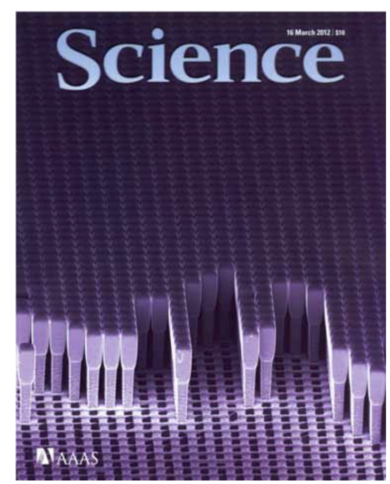
- **Blue wavelengths require thinner backside window** – enables access to lower redshift Ly-α forest for BAO

R&D needed:

- Challenge for the NIR is transparency. Thicker Si improves QE in red (650 µm, V_{sub} >200V, 20 kΩ-cm has been tested at LBNL with good success)
- Challenge for the blue is absorption in surface dead layer – Molecular beam epitaxy (δ–doping) *Applied Physics Letters*, **61**: 1084 (1992)
- Hybrid possibilities:

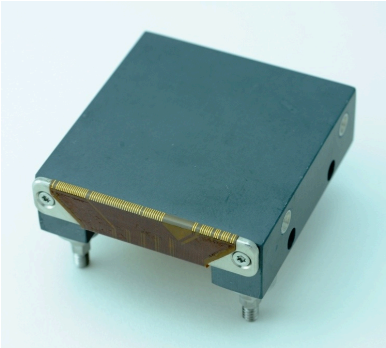
  Ge on silicon pillars with no interface defects extends response to 1.5 um

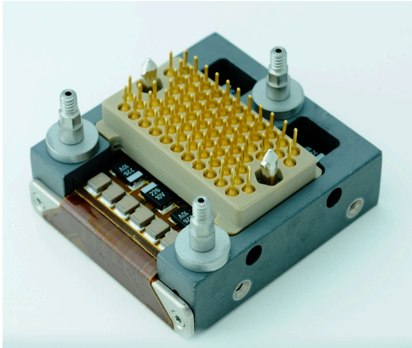
  Large band gap materials – SiC, AlN, GaN may extend response for UV-EUV.

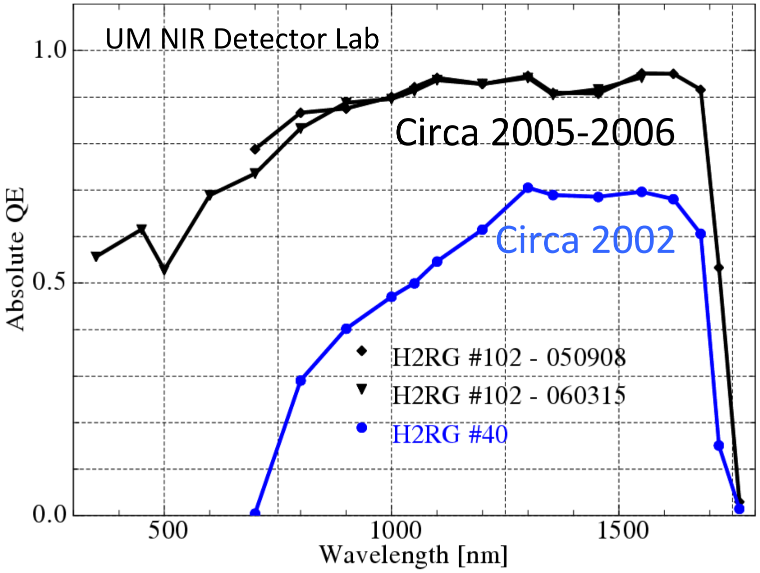


HgCdTe NIR Focal Plane Arrays (FPAs)

- Four side buttable SiC package developed as part of DoE R&D program is now standard on all TIS HgCdTe NIR detectors (Euclid, WFIRST…)
- NIR R&D efforts lead to significant improvements of detector QE: Recipe, Implant geometry, substrate removal, AR coating
- ‘Reset Anomaly’ from NICMOS devices was eventually understood as local heating effect and was mitigated by continuous clocking.
- Reciprocity failure (discovered on HST NICMOS instrument). Measured signal for a fixed # of photons depends on flux! 20% effect on some devices. Spatial variation. Large temperature variation (effect significantly reduced below ~100K) Still not yet fully understood – charge trapping or leakage suspected.

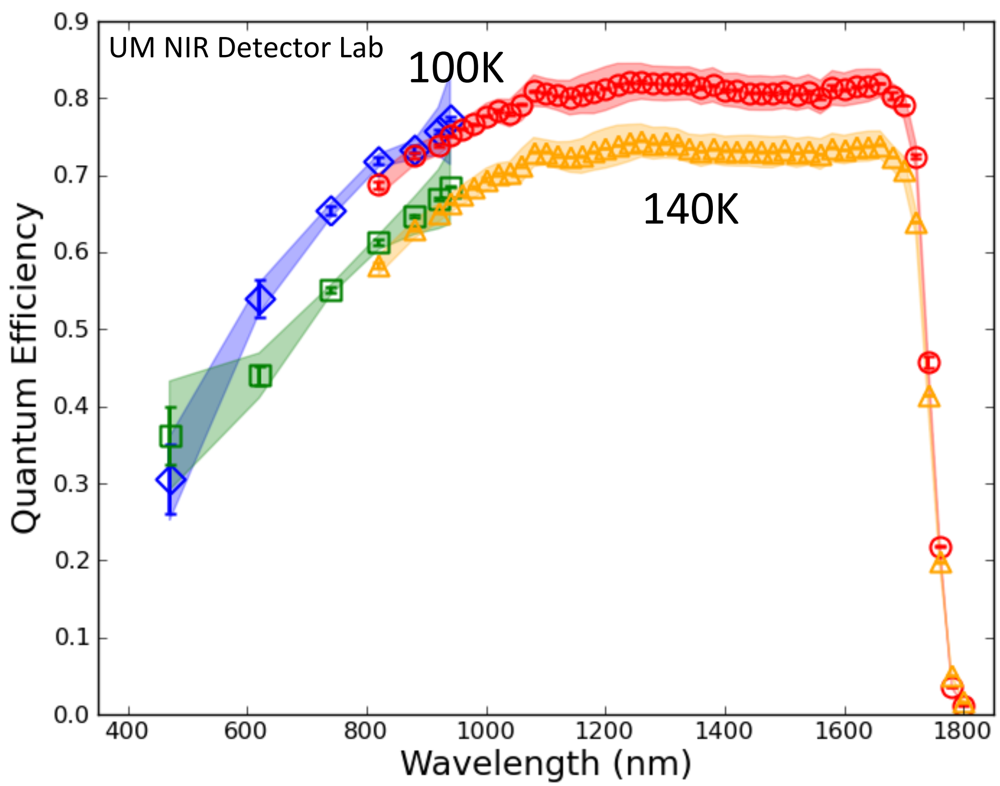






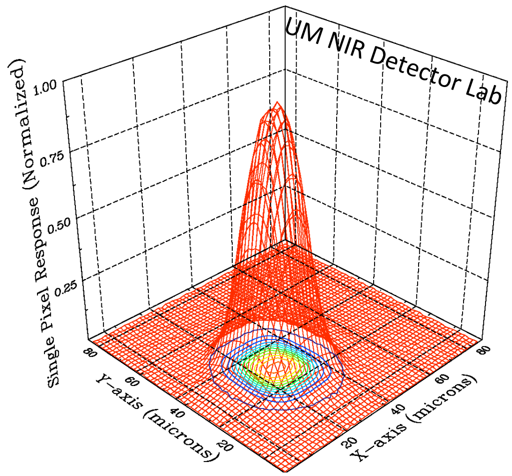
Quantum Efficiency

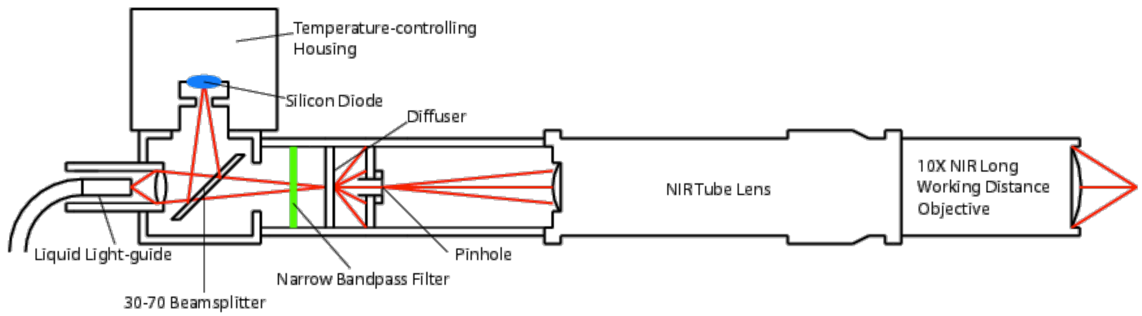
- Characterizing absolute QE is not simple!
- Temperature, reciprocity failure, bias voltage, well fill… all need to be considered
- Example: Apparent QE at 100K (blue and red) is 12% larger than at 140K (green & yellow). Difference likely due to reduction of reciprocity failure at low temperature.

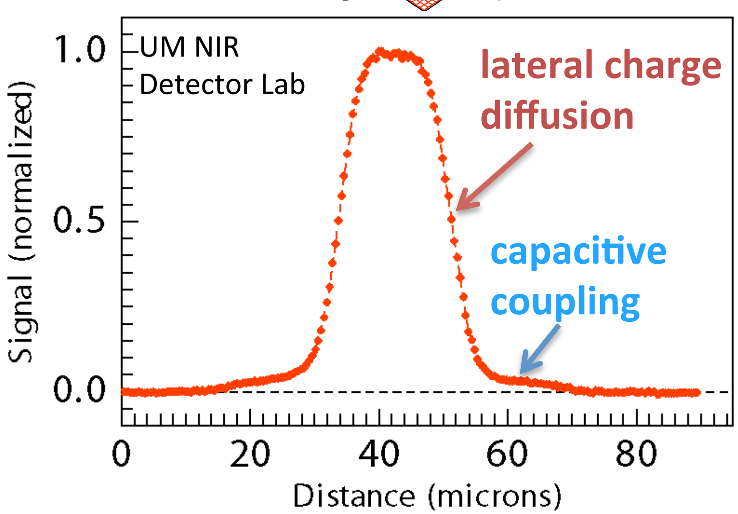


Intrapixel Response

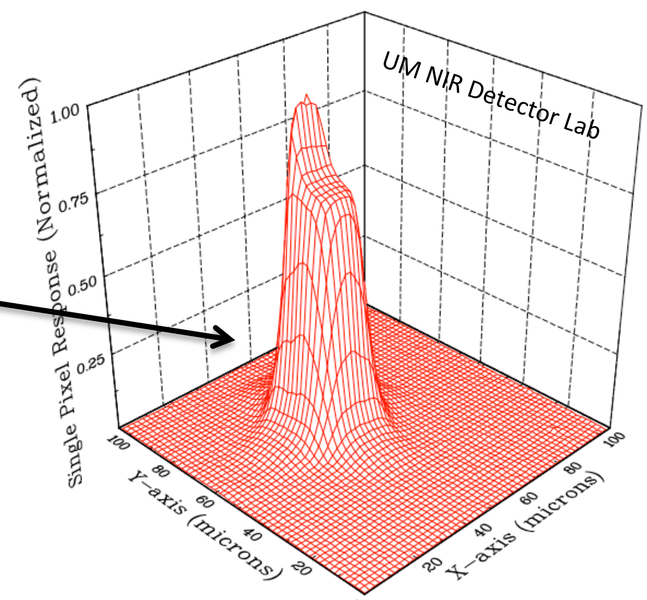
- Uniform response required for precision photometry and shape analysis for weak lensing with under-sampled detectors (required for survey speed).
- Micron-size point projection system uncovers sub-pixel structure, measures pixel size, charge diffusion and capacitive coupling.



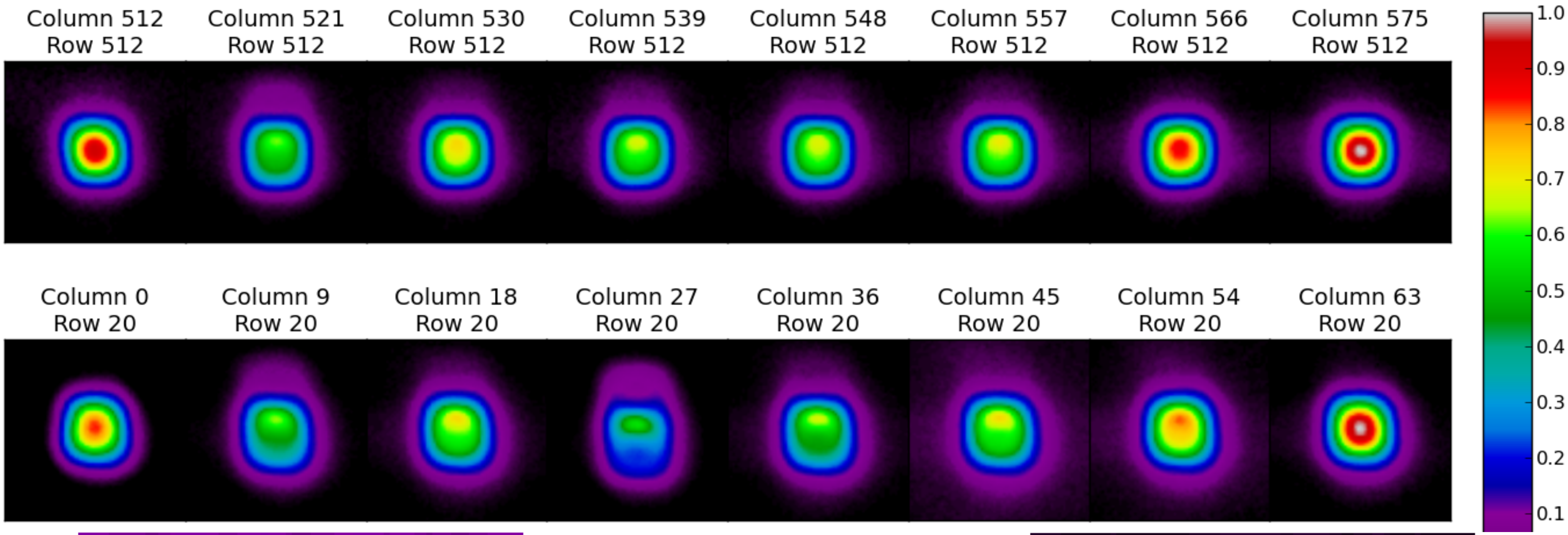


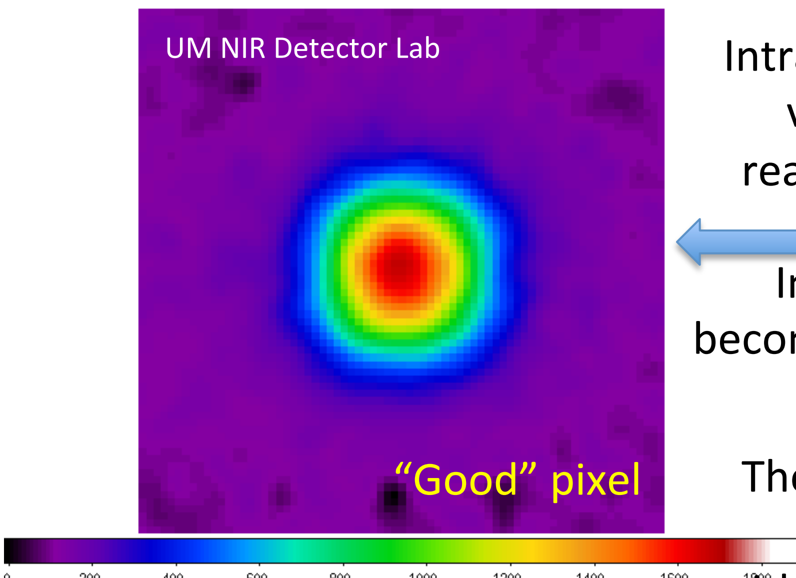


BUT some detectors/pixels are strange!



Intrapixel Structure Variations

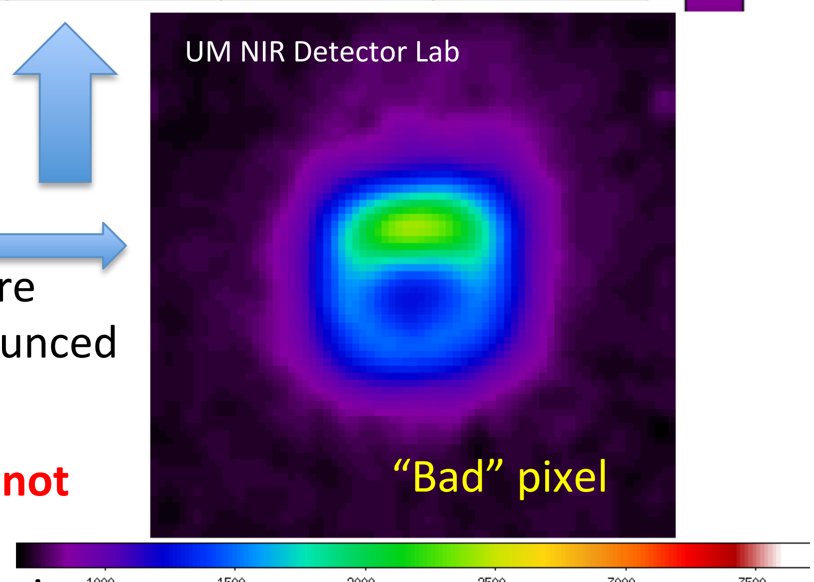




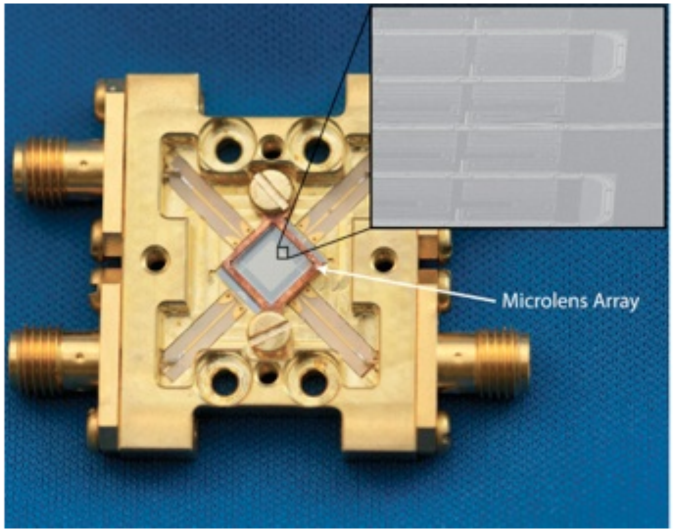
Intrapixel structure varies across readout channels

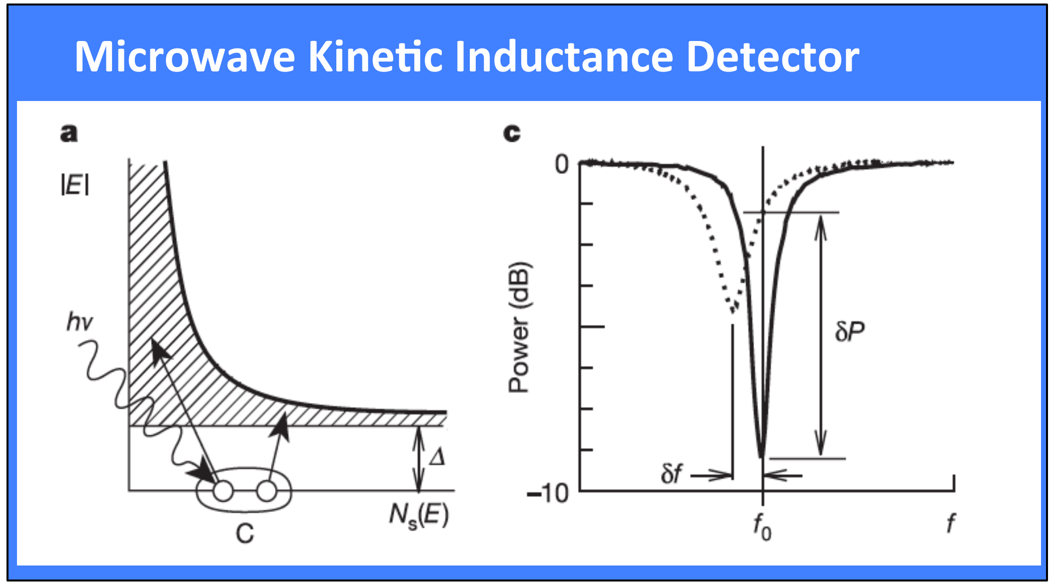
Intrapixel structure becomes more pronounced at full well

These features are **not** revealed with flatfield illumination



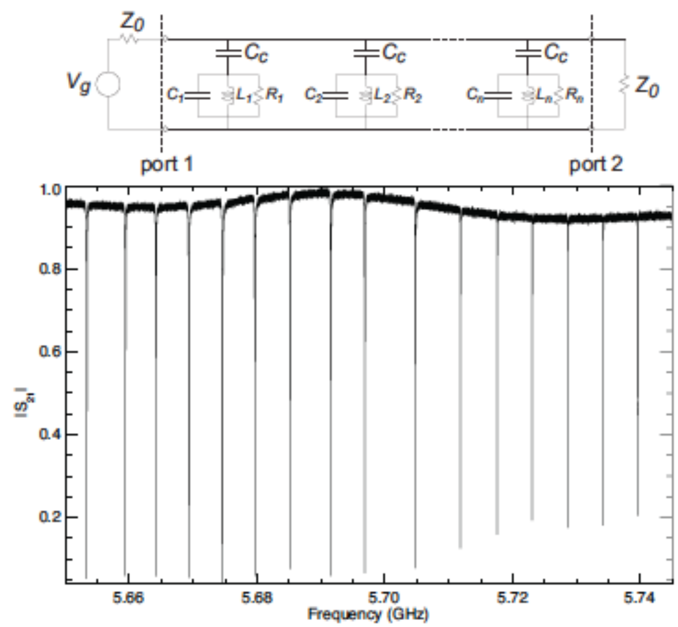
Microwave Kinetic Inductance Detectors (MKIDs)





- Transmission lines with superconducting pixels incorporated into individual resonant circuits.
- Individual photons with energy E (~ev) >> Δ (~meV) generate thousands of quasiparticals altering the kinetic inductance of a pixel and shifting the resonant frequency proportional to the photon energy.
- Optical MKIDs developed by UCSB and tested in a small astronomical instrument 1k pixels in 2011, “2k” pixels in 2012.

operating temperature = 100 mK



MKIDs - Future

MKIDs may enable large arrays of superconductor pixels, with energy resolution for each individual visible photon.

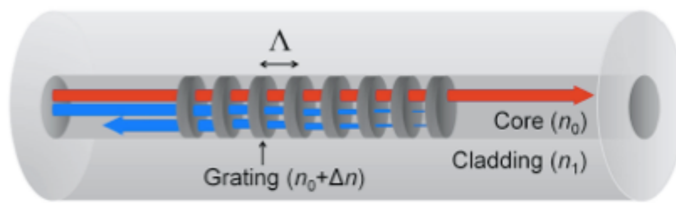
Ideal instrument for a wide field low-resolution spectroscopic survey.

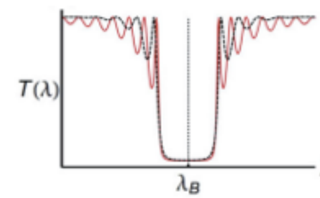
Areas of R&D that need more work to make this possible:

- **Energy resolution.** For the prototype instruments $R = \lambda/\Delta\lambda \sim 10$, in theory we can achieve R~100. Need to work to make this a reality.
- **Number of channels per feed line** is currently limited by digital signal processing and ADC speed. For a large array we need (100 parallel 20 GSPS 8 bit ADC) 2 TBytes/sec (Data rates on the scale of a particle physics experiment).
- **MKID packaging** is not mechanically or thermally viable for a large array.

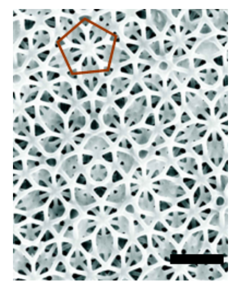
OH Line Suppression

- OH sky-line suppression may enable ground-based "clear sky" NIR spectroscopy for SNe and WL that would ordinarily require a space platform
- Technologies
  - Fiber Bragg gratings



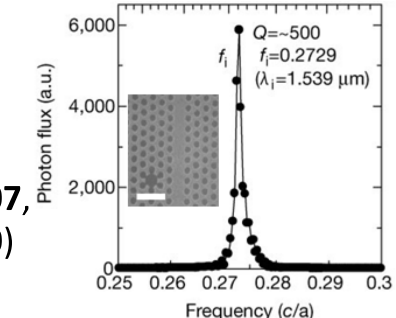


  - Quasi-crystals, "disordered photonic heterostructure"



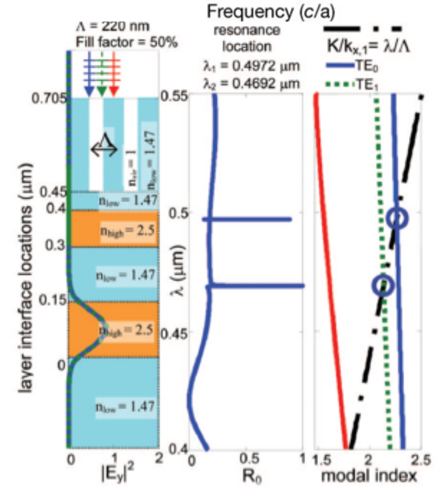
Nature Materials **5**, 942 (2006)

Nature **407**, 608 (2000)



  - Guided Mode Resonance Filter

Applied Optics, **46**, No 25, 6358 (2007)



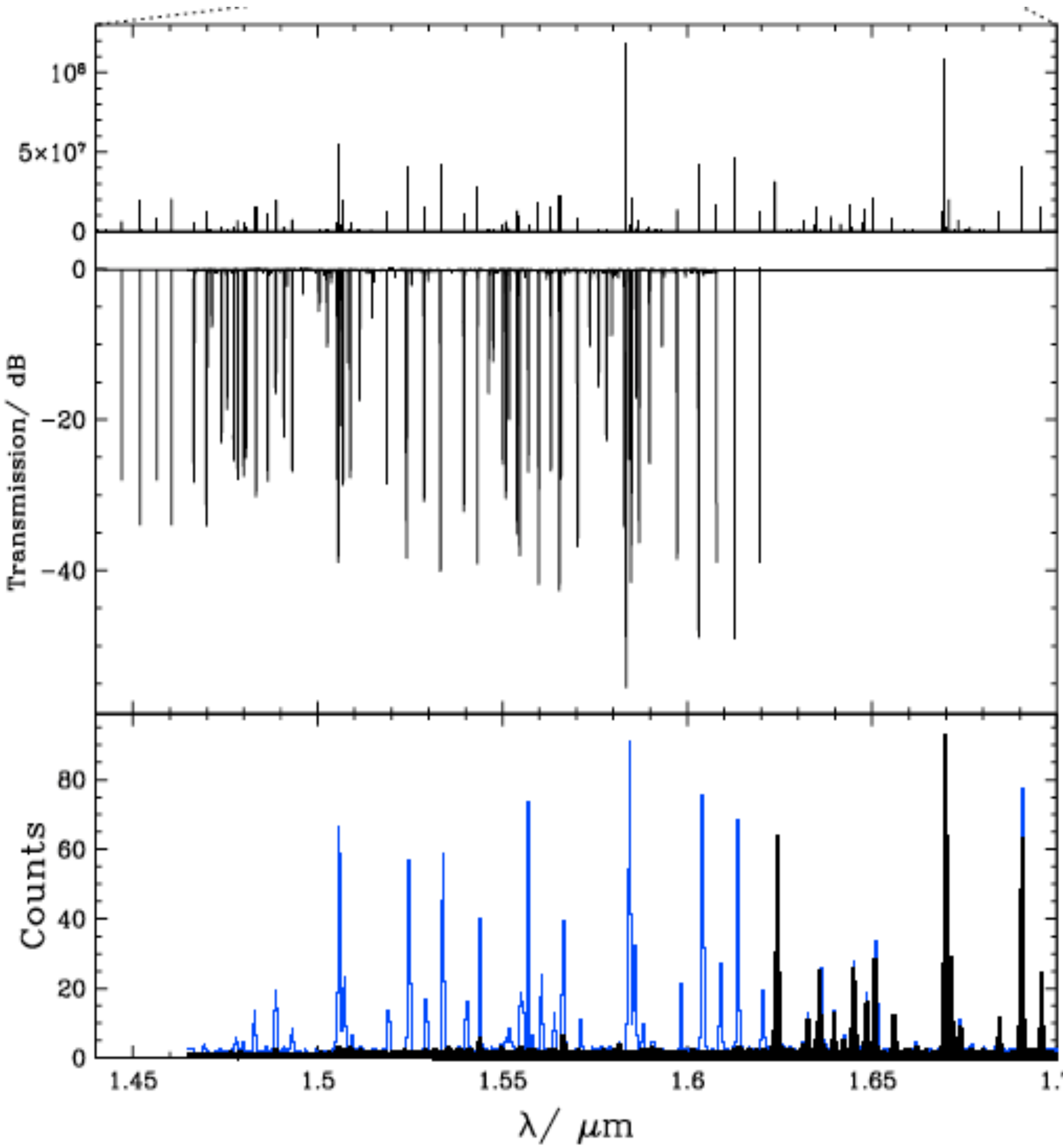
  - Metamaterials (cloaking devices)

Fiber Bragg Grating

Model of the night-sky spectrum
NIR wavelengths, illustrating the strong OH emission lines.

The measured transmission of a fiber Bragg grating.
63 OH lines are suppressed from 1.44 to 1.63 µm, and the match to the model sky spectrum is excellent.

Results of an on-sky demonstration.
Blue - night sky spectrum as measured by a “control” fiber.
Black - sky spectrum after suppression by the Fiber Bragg Grating.



Calibration

- Precise instruments require precise calibration!
- Future DE photometric surveys will require precision at better than 1% to achieve FoM goals.
- Future DE spectroscopic surveys will need $R = \lambda/\Delta\lambda > 1000$ to achieve FoM goals.
- Calibration and characterization must be done to the detectors prior to deployment to uncover subtle effects that cannot be teased out with on-sky data.
- Calibration hardware must be developed that can maintain precision at these levels throughout the survey.

This is a major R&D challenge!

Summary

- CCDs and NIR detectors mature technology BUT require sophisticated characterization studies to achieve required precision for future DE missions (EUCLID, WFIRST…)
- MKIDs promising new technology to enable simultaneous spatial and spectral measurements for future DE surveys. Will require substantial R&D effort to allow for practical implementation on a large scale.
- OH line suppression technologies may enable precision NIR observations from the ground.
- Precision calibration is essential for precision measurements
- Particle physics culture (scientists who will analyze the data develop the instrumentation) has the highest chance of success in the high precision era of dark energy measurements.

None of this will happen without a vigorous detector R&D program!